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Remote Measurement of Sulfur Dioxide Emissions Using an Ultraviolet Light Sensitive Video System

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16. ABSTRACT

Remote measurements of sulfur dioxide emissions were made using a portable ultraviolet UV light sensitive video system. The instrument system measures the UV light attenuation caused by sulfur dioxide in the effluent plume and relates this absorption to the sulfur dioxide concentration. Laboratory and field tests were conducted to establish the potential for using this technique for rapid surveillance of sulfur dioxide emissions. The laboratory studies included testing by viewing cells containing known concentrations of sulfur dioxide and measuring the emissions from a modified smoke generator. The field study was performed in two stages. Sulfur dioxide emissions were measured at a typical coal-fired power plant (concentrations ranged from 80 to 365 ppm). The elevated concentrations were obtained by reducing flue gas scrubber efficiencies. The second stage involved participation in an urban particulate modeling study which involved routine sulfur dioxide emissions measurements at 12 industrial sites.

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Remote Measurement of Sulfur Dioxide Emissions Using an Ultraviolet Light Sensitive Video System

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Remote measurements of SO_2 emissions and plume velocities were made with a portable ultraviolet light-sensitive video system and compared with EPA in-stack compliance measurement methods. The instrument system measures the ultraviolet light absorption of SO_2 and movement of SO_2 fluctuations in the effluent plume and relates these measurements to the SO_2 concentration and velocity of the plume. Laboratory and field tests were conducted to establish the potential for using this technique for rapid surveillance of SO_2 emissions. The laboratory studies included testing by viewing cells containing SO_2 of known concentrations and by measuring SO_2 emissions from a modified smoke generator. Ultraviolet absorption measurements of SO_2 concentrations ranging from 0 to 1614 ppm were made using the generator. The effects caused by submicron aerosols also were investigated. The field tests were performed on two occasions. On the first occasion, SO_2 and plume velocity measurements were made at a typical coal-fired power plant with flue gas desulfurization (FGD) controls (concentrations ranged from 80 to 365 ppm). The elevated concentrations were obtained by reducing FGD efficiencies. The second occasion involved participation in an urban particulate modeling study, which resulted in routine SO_2 emission measurements performed at 12 industrial sites. The results of smoke generator and field tests indicate that the sulfur dioxide concentration of smoke stack emissions can be made with an accuracy less than ±120 ppm (relative to the EPA stack test compliance method), provided the particulate opacity of the emissions is less than 22 percent. The velocity measurement feature of the instrument correlated poorly with the EPA compliance method for stack gas velocity.

The impact of sulfur dioxide (SO_2) emissions on the environment is a growing concern. As a result, the monitoring of this pollutant has become increasingly important. SO_2 emissions can increase as the combustion of fossil fuels increases. This occurrence is especially common when higher sulfur-content fuels are used to produce electricity. Conventional methods for SO_2 emissions analysis generally require collection of a sample for subsequent instrumental or wet chemical analysis; therefore, direct access to the industrial site is required. Ultraviolet (UV) light-absorption measurement techniques allow for the possibility of rapid source emissions analysis without the need for effluent sample collection or plant access.

A UV light-sensitive video system has been developed to make remote measurements of stack emissions. The Visiplume Model 121 SO_2/velocity monitor designed by Research Ventures, Inc., (Williamsburg, VA) measures the UV light attenuation caused by the presence of SO_2 in the effluent plume and relates this absorption to the SO_2 concentration. The monitor also was designed to measure effluent velocity by tracking concentration eddies in the plume and to determine UV opacity by measuring the ratio of UV radiation in and beside the plume.

This project evaluates both the accuracy and precision of the UV measurement method. The measurement technique and the portability of the system were studied to establish its utility for rapid surveillance of SO_2 emissions during urban modeling studies and enforcement activities. To accomplish these goals, the Visiplume system was subjected to a variety of laboratory and field evaluation tests. The laboratory study included testing by viewing transparent cells containing SO_2 and by measuring the emissions from an artificial SO_2 source.

The field study was conducted on two different occasions. The first occasion involved tests at a coal-fired power plant. During these tests, SO_2 emissions were selectively elevated by reducing the collection efficiencies of the flue gas desulfurization (FGD) system. The second occasion of the field study involved participation in an urban modeling study conducted by the U.S. Environmental Protection Agency (EPA). During this study, the Visiplume system was used to measure emissions on a routine basis at 12 industrial sites.

Experimental Methods

Instrumentation Description

The Visiplume Model 121 SO_2/velocity monitor is a UV light-sensitive video system that displays an image of a plume that is created by the UV absorption of SO_2 in the plume against the plume's UV background. The system is comprised of two major components: the optical unit with a tripod and the electronics unit (see Figure 1). The optical unit contains a vidicon camera, bandpass filters, a calibration cell, and a telephoto lens. The front cylindrical section houses the UV telephoto lens. A clip-on cover containing a filter screen can be mounted in front of the lens to provide protection and attenuation on bright days. The central rectangular section of the optical unit houses the various optical

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components. The rear section of the optical unit houses the UV vidicon camera. This section is also equipped with a sun shield to protect the camera from excessive heat buildup.

The electronics unit houses a microprocessor, analog-to-digital sampling electronics, and a digital correlator. The front panel layout contains a television monitor, a keyboard, cursor positioning controls, and a printer. Power for the Visiplume system is supplied by an internal rechargeable battery pack or 120-V alternating current.

Methodology

The spectral characteristics of the SO_2 absorption band, atmospheric absorption, and the positions of the two interference filters employed in the Visiplume system are illustrated in Figure 2. The in-band interference filter (channel B centered at 310 nm) is located just within the SO_2 absorption band, and the adjacent-band filter (channel A centered at 340 nm) is located just outside the SO_2 absorption band. Interferents of potential concern include the effects of particles and the light absorption by NO_2. These effects are essentially uniform for the two wavelength regions; the nearest absorption band for NO is 289 nm.

The SO_2 concentration is determined by measuring the light radiances for both the plume and its background (using channel B); these results are used to obtain the attenuation caused by the plume. Corrections (using channel A) are made for particulate attenuation and other scattering effects. In practice, a radiance ratio is made between the plume and background radiances in each channel, which is related to the SO_2 concentration by the following relationship:

$$Z = -\frac{T \cos\theta}{C_B L_0} \ln \frac{R_B - D}{R_A - D}$$

where Z = SO_2 concentration (ppm)
T = plume temperature (°K)
θ = elevation angle of the optical unit
C_B = a calibration factor containing the effective value of the SO_2 absorption coefficiency averaged over the channel B filter bandpass. This quantity is automatically computed from stored calibration constants and compared with an internal calibration cell.
L_0 = internal diameter of the stack exit (m)
R_B, R_A = radiance ratio, channel B or A, respectively, between the plume radiance and the background radiance
D = path radiance correction $[D = 1 - e^{-K_B S})]$. This correction term contains the UV atmospheric attenuation coefficient K_B (km^{-1}) and the range S (km).

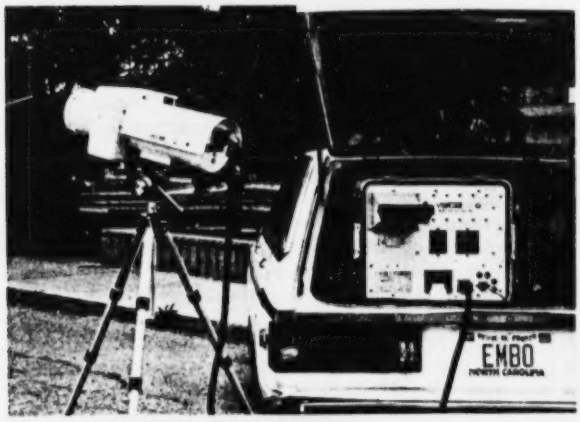

Figure 1. The Visiplume 121 monitoring system.

Effluent velocity can be measured by monitoring and tracking fluctuations in the effluent stream. The Visiplume system measures the average time required by the fluctuations to move a given distance. The resulting velocity is referred to as the eddy convection velocity.

The basic operation of the Visiplume system is greatly simplified because of its electronic capabilities and the UV image display. For a typical measurement, the operator can use the video display to sight and focus upon the desired target. Using the keyboard, the operator inputs the following target parameters: effluent temperature, internal stack exit diameter, and UV atmospheric attenuation coefficient. The atmospheric attenuation coefficient is approximated using a chart supplied by the Visiplume manufacturer or can be determined from visibility readings obtained locally (e.g., from airports). A cursor pattern is automatically computed and displayed on the video monitor. Using cursor positioning controls, the pattern can be properly positioned as shown in Figure 3; the separation of the two point cursors is equal to one stack diameter. For an SO_2 concentration measurement, both in-band and adjacent-band intensity measurements are made at each point. For velocity determination, measurements are made along the vertical line cursor. This line is composed of 64 points and is programmed to be 0.6 × stack diameter in length. Fluctuations (eddies) in the SO_2 concentration are tracked along this line measuring the average time required to move a given distance, i.e., the velocity. The SO_2 concentration, velocity, SO_2 emission rate, operator inputs, calibration error, and time and date are output to both the video display and the printer.

Laboratory Measurements

Tests were conducted using a test bag system that consisted of a twin cell chamber containing two inflatable Teflon bags. One bag contained air, while the other initially contained air and then contained various concentrations of SO_2. The measurement pathlength was 45 cm (18 in.). The first three tests were conducted outdoors with the test bag system positioned 8 m (26 ft) from the Visiplume, and the sky could be viewed through each bag simultaneously. The remaining seven tests were conducted indoors using an artificial UV light source (a Sylvania F8T5/BLB fluorescent lamp). The spectral output of this bulb displayed sufficient intensities at the required wavelengths for the Visiplume system to operate properly. One set of bags was tested under both conditions; no significant differences resulted. Each test consisted of 10 Visiplume measurements of the test bags and five measurements of only the background UV (sky or blacklight). After each test, the SO_2 bag was removed and an EPA Reference Method 6 test (Determination of Sulfur Dioxide Emissions from Stationary Sources)[1] was conducted on the gas within the bag. Table I lists all laboratory and field tests and comparative measurement results.

The next progression of tests was conducted outdoors using a combination of equipment. An anhydrous SO_2 injection system was installed upstream from a smoke generator blower. The modified smoke generator was used to develop a controlled SO_2-laden effluent, which was exhausted at constant velocity out of a 30-cm (12-in.) diameter stack. A series of 13 simultaneous Visiplume, Method 6, and EPA Reference Method 2 (Determination of Stack Gas Velocity)[2] tests was conducted over a wide range of SO_2 concentrations with no aerosols present (Table I). Each test consisted of a minimum of five Visiplume measurements taken during Method 2 and Method 6 sampling. All Visiplume measurements were made at a range of 12 m (40 ft) from the stack exit.

The final aspect of laboratory testing investigated the effects of aerosols on the measurement of SO_2. Using the smoke generator/SO_2 injection system, it was possible to produce either a black (soot) or a white (condensed oil droplet) smoke of any selected opacity with the presence of SO_2.

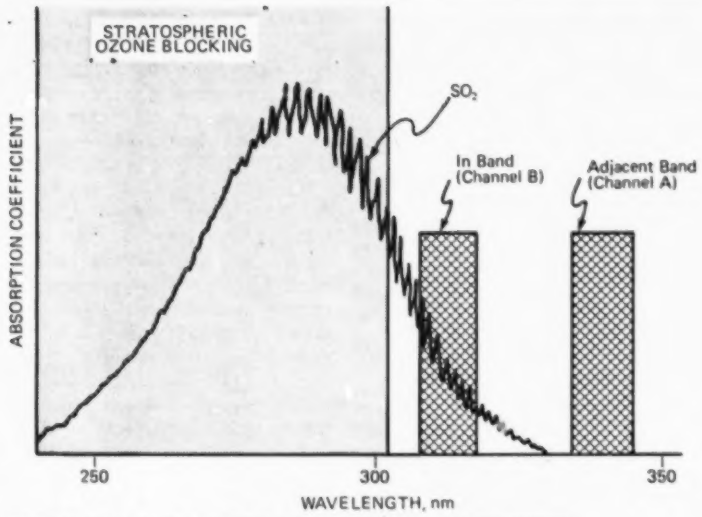

Figure 2. Sulfur dioxide absorption spectrum and Visiplume filter positions.

The opacity was measured by a stack-mounted transmissometer. Particle sizing tests[3] indicated that both smokes had an average diameter of less than 1 μm.

Smoke interference tests were initiated by setting and maintaining a constant SO_2 mass flow rate. Visiplume measurements were taken of this emission without the presence of smoke. Then smoke was introduced and its opacity was incrementally increased. A series of Visiplume measurements was taken of the constant SO_2 emission with every increment of opacity. This procedure was repeated until the Visiplume readings were significantly affected by the presence of smoke. Both black and white smokes were tested in the same manner (Table II).

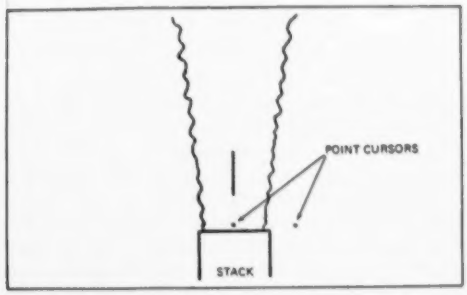

Figure 3. Correct cursor pattern position.

Field Measurements

A field study was conducted at a coal-fired power plant (No. 1) that consisted of four generating units. The particular unit tested was nominally operated at a 260-MW output. The SO_2 and particulate-laden effluent was passed through an FGD system. The cleaned effluent was then exhausted out through a masonry stack that was 107 m (350 ft) tall and had a 4.9-m (16-ft) diameter exit. Visiplume measurements were made at a range of 400 m (1312 ft) from the stack exit. Over the course of testing, the SO_2 emission level was selectively elevated by partially bypassing the FGD system to obtain a range of concentrations. Visiplume SO_2 and velocity measurements were compared with the results obtained from on-stack Bendix continuous SO_2 monitor and Method 2 tests (Table I). The continuous Bendix monitor had undergone recent calibration tests, and the results show that the Bendix measurements were within 10 percent of Reference Method 6 results.

Visiplume measurements were taken during a Philadelphia Urban Modeling Study being administered by EPA. During a two-week period, the Visiplume system was used to obtain routine SO_2 emissions measurements at EPA-designated sources located in the Philadelphia-Wilmington area. Tests at 12 designated industrial sites resulted in measurements of emissions from 29 different smoke stacks. The type and quantity of sources were one coal-fired power plant (two stacks), one coke-fired power plant (five stacks), two oil-fired power plants (eight stacks), two refuse incinerators (four stacks), one antimony roasting plant (one stack), three refinery fluid catalytic crackers (four stacks), and two residual oil boilers (five stacks).

One aspect of this study sought to determine the Visiplume system's potential for rapid surveillance of source emissions. A compact hatchback automobile was used to

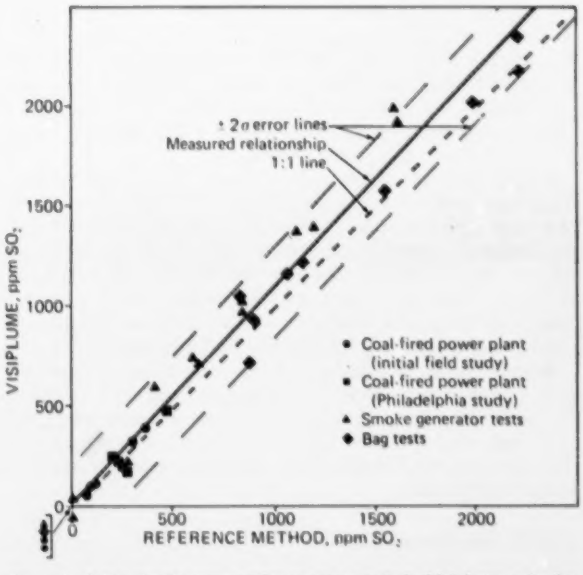

Figure 4. Sulfur dioxide comparative measurements by Visiplume and reference methods.

Table I. Sulfur dioxide and velocity measurements for various laboratory and field tests.

Test	No.	SO_2 (ppm)		Velocity (m/s)	
		Visiplume	Method 6	Visiplume	Method 2
Inflated bag	1	938	889		
	2	1049	825		
	3	726	881		
	4	2020	1983		
	5	2356	2203		
	6	2177	2215		
	7	1584	1545		
	8	1221	1135		
	9	1163	1057		
	10	24	0[a]		
Smoke generator	1	718	635	7	9
	2	748	605	2	9
	3	981	845	−1	9
	4	1035	849	15	9
	5	1404	1201	12	9
	6	1379	1114	11	9
	7	1932	1614	12	9
	8	1988	1588	4	9
	9	600	418		
	10	225	272		
	11	51	16		
	12	−48	5		
	13	29	0[a]		
Coal-fired power plant No. 1	1	63	79[b]	27	21
	2	99	102[b]	29	21
	3	120	130[b]	28	21
	4	394	365[b]	36	21
	5	326	306[b]	36	21
	6	10	0[a]		
Coal-fired power plant No. 2	1	226	238	25	11
	2	227	232	20	12
	3	205	269	21	12
	4	198	270	30	11
	5	223	271		
	6	476	471[b]		
	7	19	0[a]		

[a] Visiplume zero calibration measurement.
[b] Determined by in-stack SO_2 continuous monitor.

transport the Visiplume system between sites. At each measurement site, the optics unit and tripod stand were placed on the ground at the rear of the vehicle and connected to the electronics unit located in the hatchback area of the car. Total set-up time was approximately 5 min. Time required to calibrate and obtain a set of SO_2 emission measurements at each site was approximately 30 min per stack. Each set consisted of a minimum of 10 measurements of emissions from each stack. During the course of a day, as many as six EPA-designated sites were visited.

Comparison measurements of SO_2 and velocity by both Visiplume and in-stack measurement tests were conducted at a coal-fired power plant (No. 2) during the Urban Modeling Study. All measurements were taken of effluent exhausted out a masonry stack that was 76 m (249 ft) tall with a 5.6-m (18-ft) diameter exit. Tests were performed to compare results of Visiplume measurements with those from an acid condensation system[4] and with Method 2 (Table I). The acid condensation system included a condenser that trapped the acid, followed by a peroxide midget impinger train (Method 6) that trapped SO_2. Also, one Visiplume test was conducted and compared with the in-stack SO_2 continuous monitor. The required stack parameters were obtained from the EPA stack testing team.

Results and Discussion

A comparison of SO_2 concentration measurements by Visiplume and reference methods is shown in Figure 4, which includes the results of the test bag system, smoke generator, and two field tests. The regression line of all data, the 1:1 line, which represents ideal agreement, and the 2σ standard error lines are also shown in the figure. The standard error estimate bands represent the estimate of twice the deviation of Visiplume measurements about the regression line.

The comparison shows that in the 36 tests, ranging in concentration from 0 to 2215 ppm SO_2, Visiplume measurements are in good agreement with the reference measurement method. The calculated regression slope of 1.08 with a correlation coefficient (r) of 0.989 demonstrates good statistical agreement. The 2σ standard error lines represent a range of ±210 ppm for Visiplume measurements. Manufacturer claims for Visiplume SO_2 concentration measurement accuracy are ±5 percent of full scale (3000 ppm) or ±150 ppm. Data show that 31 of the 36 tests were within the manufacturer-claimed limits; i.e., 86 percent of the data were within ±150 ppm of the reference SO_2 concentration measurements.

The regression analysis of data for each type of study (test bag, smoke generator, or field source) is presented in Figure 5. The test bag data were taken over an SO_2 concentration range of 0 to 2215 ppm. An analysis of 10 tests shows a regression slope of 1.00 with an r value of 0.989 and a 2σ standard error range of ±218 ppm. The smoke generator data were taken over a range of 0–1614 ppm SO_2. An analysis of 13 tests shows a regression slope of 1.22 with an r value of 0.997 and a 2σ error range of ±116 ppm. Field data acquired at two sites were taken over a range of 0 to 471 ppm SO_2.

Table II. Smoke interference tests comparing Visiplume sulfur dioxide measurements at various opacity levels of black and white smokes.

Test No.[a]	Visiplume SO_2 (ppm)	Transmissometer % opacity	Visiplume response, %
B-1A	1036	0	100.0
B-1B	981	8	94.7
B-1C	895	16	97.3
B-2A	979	0	100.0
B-2B	970	21	99.1
B-3A	901	0	100.0
B-3B	501	28	55.6
B-3C	666	23	73.9
B-3D	871	22	96.7
B-3E	684	23.5	75.9
B-3F	501	26	55.6
W-1A	869	0	100.0
W-1B	926	9	106.6
W-1C	894	14	102.9
W-2A	755	0	100.0
W-2B	726	20	96.0
W-2C	472	22	63.0
W-2D	250	26	33.0

[a] B—black smoke; W—white smoke.

Statistical analysis of 13 tests shows a regression slope of 0.98 with an r value of 0.974 and a 2σ error range of ±66 ppm. The comparison of field and reference method results shows that they agree very well, although the range of the field data was limited. The scatter of the results, as indicated by the 2σ errors, was somewhat greater for the series of smoke generator tests than for the field data. An analysis of smoke generator tests over the restricted range of 0–635 ppm SO_2 (seven tests) shows a regression slope of 1.21 with an r value of 0.981 and a 2σ error range of ±147 ppm. The SO_2 measurement is based upon attenuation per unit pathlength. Therefore, the shorter the pathlength (plume diameter), the lower the precision of this measurement.

The effects of the presence of submicron aerosols on Visiplume SO_2 measurements are shown in Figure 6. The results are plotted as Visiplume response (percent) versus transmissometer readings (percent opacity). Two curves are drawn that represent a visual approximation of these relationships. Visiplume response is determined by the following equation:

$$VR = Z/Z_0(100) \qquad (2)$$

where VR = Visiplume response

Z_0 = initial Visiplume SO_2 measurement with no smoke present

Z = Visiplume SO_2 measurement in the presence of smoke

The results show that the presence of black or white smoke up to approximately 22 percent opacity had no significant effect on the Visiplume measurement. However, higher opacities became a distinct interference as evidenced by the drop of the Visiplume response values.

The test results of the Visiplume velocity measurements with stack velocities (Figure 7) show that Visiplume velocity measurements tended to be high compared to stack measurements. A linear regression slope of 1.77 with a correlation coefficient of 0.806 was observed. The 2σ standard error lines represent a range of ± 14.4 m/s for Visiplume results.

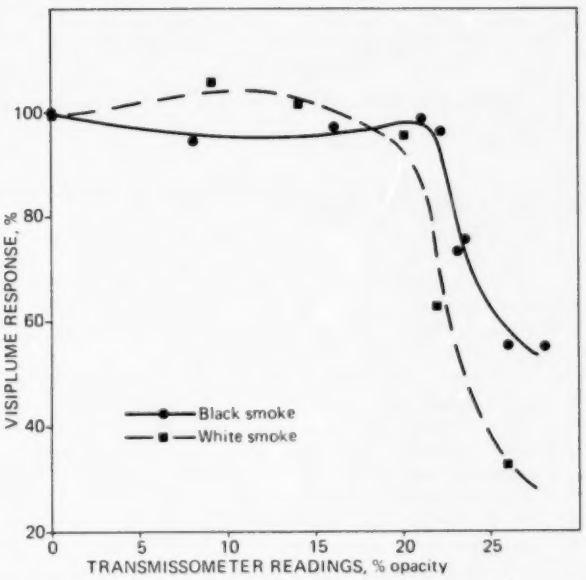

Figure 6. The effects of smoke on the Visiplume sulfur dioxide measurement.

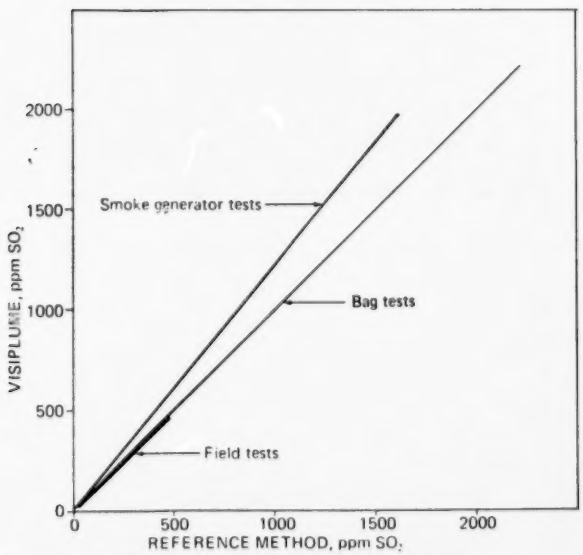

Figure 5. Linear regression analysis for each major test type.

The statistical results demonstrate a wide scatter of data. The reason of these results has not been determined. However, it was suspected that insufficient turbulence (eddies) existed in the plume.

Conclusions

The comparative measurements by Visiplume and Method 6 demonstrate the potential use of UV light absorption measurements to determine SO_2 concentrations. Experimental data obtained from laboratory and field sources indicate that the SO_2 concentration of smokestack plumes can be accurately determined by measuring the attenuation of atmospheric UV light caused by the presence of the SO_2 gas. The laboratory and field results agree very well with the reference method results. The somewhat greater 2σ standard error values for the laboratory data, compared with those for the field data, may be attributed to a combination of the measurement pathlength and SO_2 concentration range differences. The Visiplume SO_2 reading is based upon the UV absorption per meter pathlength. Therefore, the greater the plume diameter, the greater the precision and accuracy of the SO_2 absorption measurement.

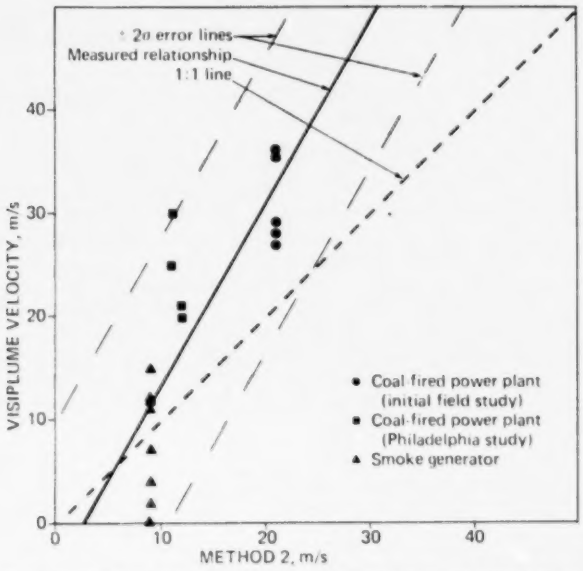

Figure 7. Visiplume velocity measurements versus Reference Method 2 results.

As a qualitative review, this system exhibited very good versatility and utility for making field measurements. Measurements were taken on clear, cloudy, and completely overcast days with no significant effects if sufficient UV intensities were available. This sufficient UV intensity requirement causes the operating period to be shorter during the winter months. Error messages will be displayed if insufficient or excessive UV intensities are present.

The only significant problem occurred when the camera and control unit required protection from excessive heat. A fan installed on the control unit appears to have alleviated the problem. To enhance field compatability further, the internal battery pack of the instrument could be removed from the control package and housed in a separate container, or the battery pack could be replaced by a Visiplume-to-automobile umbilical connection (12V). Either adaptation will significantly reduce the weight of the control unit and thereby increase the portability of the Visiplume system.

The measurement of velocity using the Visiplume method demonstrated some monitoring technique problems. The major problem involved the velocity-tracking cursor. The Visiplume model design used for this test could monitor only vertical flows, and thus could not compensate for the wind shear effects, which may quickly bend a plume. Also, in some cases, a small plume may not create sufficient boundary turbulence to create eddies; therefore, velocity tracking is inhibited. Discussions with the manufacturer indicate that further development of this technique is under way.

Disclaimer

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